Renewable and Sustainable Energy Reviews 13 (2009) 1994–2002

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Development of a Life Cycle Assessment Program for building (SUSB-LCA) in South Korea

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ARTICLE INFO

Article history:
Received 9 October 2008
Accepted 13 January 2009

Keywords:
SUSB-LCA
Life Cycle Assessment
Energy
CO_2

ABSTRACT

Our environment is an important resource, not only for use in development, but to conserve. In the 1990s, the importance of our environment became underscored for conservation efforts in many areas. Among them, the building construction industry had played a role in impoverishing the environment, for the sake of improving our quality of life, but at a great cost of impact to the environment. It is therefore incumbent upon the industry to endeavor to mitigate effects from building constructions to our environment.

During the life cycle of a building, it consumes energy and other natural resources. But it is difficult to evaluate their effects on the environment during the entire course of a building's life span, without much time and effort. An easy to handle program is necessary for the calculation of effects to the environment during the life cycle of a building. Many of the software programs developed for these kinds of assessments can only be used with significant restrictions because of their differences in design for scope and content. This paper presents foundations for the development of a Life Cycle Assessment (LCA) program for buildings, focusing on their energy consumption and carbon dioxide emission levels, with a comparison of domestically and foreign designed programs.

Contents

1. Introduction

1.1. Research background and objectives

Recent interest and efforts for the environment has emphasized its importance not as a source for indiscriminate usage, but

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doi:10.1016/j.rser.2009.01.002

to preserve it while improving human life, in a mutually supportive role. Existing constructions tended to dwell on their architectural aspect, largely unconcerned with their environmental impact which comes into play during its life cycle [1,2]. But we must not see our environment as merely a resource to be expended, but recognize its critical role as a necessary condition, and develop technology for the mitigation of impact on our environment [3].

Unlike general consumer goods, a building possesses a long life span consisting of its construction, operation & maintenance, and demolition & dismantling, consuming energy resources throughout its life cycle, and yielding environmental byproducts such as CO_2. Therefore, development of new building technology for preserving the environment is necessary, by predictive analysis and assessment of impact from energy usage and pollutant emission [4]. For this purpose, an assessment involving total analysis of the raw materials and resources used during a life cycle process, and energy usage according to the type of construction, global warming emissions such as CO_2, and production of demolition waste must be taken into consideration [5–8].

An example of method for comprehensively measuring resource and energy consumption, and environmental byproduct emissions during the life cycle of a building is the Life Cycle Assessment (LCA). It is able to quantify energy consumption and environmental pollutant emission, by defining a scope of analysis for each type of building or fabrication method, types of manufacturing or construction material, and for each stage of its life cycle. But such an analysis becomes relatively complex, with its scope expansive, and requires a disproportionate amount of effort and time for application [9–11].

This paper attempts to present a program, with its components and characteristics, for the analysis of a building, by each stage of its life cycle, construction material and energy consumption, and consequent emissions of environmental byproducts. Such a study would provide baseline data for the development of a program for LCA applications. Furthermore, through the development of a program with these baseline components and characteristics, the amount of time and effort required for LCA implementation may be reduced.

1.2. Analysis methodology

A building's life cycle can be divided mainly into stages of its construction, operation & maintenance, and demolition & dismantling. Any subsequent LCA Program would have to be able to reflect these stages of a life cycle. The method of analysis for defining the components and characteristics of an LCA Program are as follows.

First, existing similar programs available domestically and from outside were analyzed for comparison of their makeup and characteristics. More of the LCA Programs were foreign developed, but most of them were designed for the refrigerator, microwave oven and general consumer goods, or otherwise for raw materials and resources. For this paper, programs were selected for comparison and analysis as deemed pertinent for a building LCA.

Second, components of data format, as a mathematical function, required for entry in calculating energy consumption and CO_2 emission for each stage of a building's life cycle are presented. For this, the methods of analysis and their components, for input data required at each stage of the life cycle were prepared.

Third, the results of the program are presented as both measures of the total quantity and of the base units. The base unit of measure is by dimensions of an area. Moreover, energy consumption and CO_2 emission were computed for a specified period, in consideration for the age of a building.

Fourth, an example apartment building was used for validation of the LCA Program, with the results of the analyses presented in both base units and in terms of the total quantity.

2. Comparison of existing programs' characteristics

2.1. Characteristics comparison

LCA is used as a tool to offer a design alternative, in reducing a building's environmental impact, by calculating its resource and energy consumption and environmental byproduct emissions, such as CO_2, during the life cycle of a building. But it is difficult to use LCA fully as intended, for lack of a generalized calculation methodology, and insufficient database, and is mainly limited to calculations for inventory analyses of energy consumption and environmental byproduct emissions such as CO_2.

Recent LCA Program developments were intended for the construction of life cycle inventory (LCI) database for refrigerators, computers, and general consumer products. But buildings are different from general consumer products for their long life span, and possess different characteristics from consumer goods [12].

Examples of the various programs developed or commercialized for the performance of LCA are BOUSTED, ECOLOGIC, IDEA, PEMS, TEMIS, SIMAPRO, ECOPACK2000, TEAM, OfE, LIFEWAY, LCAiT, GaBi, KCL-ECO, and LCAiT. These and others add up to approximately 20 programs already completed, and many more if we include those still in development. These programs can be divided according to their usage as educational, or commercial. A perusal of the representative LCA Programs and their main components are as shown in Table 1.

Comparison analyses of existing programs for their content, handling speed, database composition and other general characteristics are as follows. These various LCA Programs show differences in terms of their development entity, and their ease of program operation. Comparison of the programs for their purpose and speed, data handling capacity, handling of uncertain variables, sensitivity analysis, and ease of operation are as shown in Table 2.

While most of the programs were expanded to include inventory analysis and impact assessment standards, they are being used for only limited parts of LCA analyses. The programs possess independent, or shared databases. The Simapro program, for example, allows manipulation of database for their national or regional characteristics through addition, deletion or changes to the database [13,14].

The Simapro program is widely used in environmental design (DfE) and LCA, comprised of a main data with process categories of material, energy, transport, processing use, waste scenario, waste treatment, etc., with each category further divided into subcategories. Once data are entered, the type of LCA to be performed is selected, then a life cycle is chosen, with the product system name for the LCA assessment. This program has a simple data entry function and easy to use for the beginner. Except for functions of data protection, the Simapro demands input of all data according to a certain format, so that in using the database produced after the LCA process, details of the database are available, and allows for the selection of database appropriate to the purpose & scope of an LCA.

The KCL-ECO program is convenient to use, with most functions performed with the click of a mouse, except for user entry of definition for the equation of input & output calculation. Database is managed by a program called "DataMaster," with over 200 modules included. Downside is there is no data protection function, but the units used in the program are user changeable. Menu should be used to enter all environmental loads before performing LCA.

Among the programs above, GaBi was constructed very similarly to the Windows system, with most all functions mouse

Table 1
LCA Programs developers and reason for development.

Type of Program	Development Organization & Major Points
BOUSTED	Best known program in Europe, developed in 1972 by Dr. Ian Bousted of England; the most comprehensive LCA Program containing over 2000 industrial data. Had originally focused on fuel and energy, but recently became possible to analyze a wide scope of materials and processes
ECOLOGIC (International Database for Eco-Profile Analysis)	Program originally developed by Austria's IIASA (International Institute for Applied Systems Analysis), now managed by Finland's VTT Technical Research Institute, and maintained as the mean data for Western Europe, allowing comprehensive analyses especially around material manufacturing, energy, and transportation
PEMS (PIRA Environmental Management System)	Program developed by the packaging industry association, capable of two functions of inventory analysis and impact assessment; originally used BUWAL and PIRA data to analyze packaged products
TEMIS	Developed by the Okoinstitute in Darmstadt, Germany, dealing with energy and transportation, and also used as a support program for energy policy legislation
Simapro	A design support program for processes and material systems, first developed by Leiden University's CML (Institute of Environmental Sciences), later revised to now include impact assessment developed in Switzerland
ECOPACK2000	Developed by England's Landbank Agency, from the BUWAL and Bousted systems, dealing mainly with packaged goods, and capable of impact assessment
TEAM (Tools for Environmental Analysis and Management)	Developed by France's Ecobilan, with database on spreadsheets for PC usability, and maintained using standard Ecobilan data called DEAMS, capable of detailed analyses of energy, transportation and materials
OfE (Okoinventare fur Energiesysteme)	Developed by Switzerland's ETE as an electric generation system program. Allows comprehensive analyses of environmental demand by petroleum, gas, coal, nuclear, aquathermal, biomass, geothermal, solar heat, and solar radiation resources, including radioactive materials
LIFEWAY	Educational program developed by the Technical University of Denmark, limited in scope, but allows for values assessment

performable. It was also structured in accordance with procedures as prescribed in ISO 14040, offering various functions to allow the user to structure the systems with ease.

Unlike other programs, the TEAM program is cumbersome for requiring the LCA process inventory analysis and LCA impact assessment to be operated separately, using DEAM and TEAM. Data protection features are similar to Simapro, with DEAM containing over 500 modules. Impact assessment database is also wide in scope, but since the impact assessment database sees each category as one database, it only proliferates the number of database for assessment within the program. It is more efficient to define beforehand the units of environmental loads prior to the execution of LCA.

Unlike other LCA Programs, the LCAiT is troublesome for requiring the input of environmental demands on the process card and transport card. However, it has the advantage of allowing the user to build a new database, since the energy and transportation databases are managed separately within the program. It does not have data protection measures. The units for environmental loads are restricted to those defined by the program, requiring the user to convert all surveyed environmental load data to that unit recognized in the program. LCAiT cannot perform comprehensive LCA of all processes. So a process is required for using an export menu to send the inventory matrix calculated from inventory analysis to an MS/Excel program to run an impact assessment. The Macro function of the MS/Excel can be used for a simple impact assessment analysis, but there is no function for a sensitivity analysis.

Currently available LCA Programs and those being developed offer a wide array of database and functions. Since each of the representative LCA analysis programs from above possesses special characteristics, it behooves the LCA user to select a program based on the scope and content of analysis, the quality of database and for compatibility.

2.2. Types of programs and database characteristics

The various LCA Programs already introduced are being used on a limited basis for general consumer products. For such applications, the LCA of all processes are expedient, but they are limited for applications of long life cycles such as buildings. Limited applications are possible for calculating emissions of CO_2 and sulfur compounds used in construction materials. Programs to be used for applications on objects possessing characteristics such as buildings can be divided into three large types.

First is a program capable of performing Life Cycle Assessment (LCA). Such programs are presented in Table 1.

Second is to facilitate analysis and assessment of energy consumption, where such programs are utilized during a building's planning, design stage for simulations to assess energy consumption. Third is an assessment scheme for reducing environmental emissions, and a program used as a decision making tool during design stages. Table 3 lists these programs.

They can also be categorized according to the methods used to build LCI database for construction materials. These are classified

Table 2
Comparison of LCA Programs.

	Intended Purpose	Speed	Computational Capacity	Uncertainty Handling	Sensitivity Analysis	Ease of Handling
Simapro	Inventory Analysis Impact Assessment	–	Average	None	None	Average
KCL-ECO	Inventory Analysis Only	–	–	Average	–	Average
EcoPro	Inventory Analysis Impact Assessment	–	Bad	–	–	Average
GaBi	All Purpose	Average	–	–	–	Average
TEAM	All Purpose	Superior	Superior	–	–	Bad
TEMIS	Energy Analysis	–	–	–	–	–
ECOPACK K2000	Packaging Analysis	–	–	–	–	–
LCAiT	All Purpose	Average	–	–	–	Average

Table 3
Program types according to intended usage.

LCA Software	Energy Usage Assessment Tools	Design & Decision Making
LCAid (AUS)	Athena (CAN)	ECOTECT (AUS)
LISA (AUS)	BUNYIP (AUS)	Equer (FR)
BEES (US)	DOE2 (US)	Building Design Advisor (US)
Boustaed (UK)	Envest (ULC)	GBTool (20 countries)
Eco Quantum (NL)	Optimize (CAN)	Green Building Advisor (US)
Gabi (DM)	Firstrate (AUS)	BREEAM (UK)
KCL-ECO (FIN)	Cheetah (AUS)	LEED (US)
LCAit (SW)	NatHers (AUS)	
PEMS (UK/US)	BREGains (UK)	
SIB LCA (DE)		
SimaPro (NL)		
TEAM (FR/US)		

Table 4
Comparison of estimation methods for original unit calculation.

	On site survey	By related industry	Mixed method
Accuracy of Result	○	□	○
Required Time	△	○	△
Scope of Analysis	△	○	○
Latest Data Update	□	△	□
Cost Consideration	△	○	△

Note: (○) Good; (□); Average; (△) Low.

as database built in terms of base units for existing on-site surveys, database built in terms of base units utilizing analysis methods by related industry, and by collecting other various data according to usage, to form one database. They are also termed direct investigation, indirect investigation, and mixed methods. A comparison of their relative advantages is shown in Table 4.

The base units according to the direct investigation method are data constructed from the tracking and investigation of the entire process for building material, from its extraction in raw form to its manufacture, through the operational period to its demolition. But such an investigation process is not only complicated, but time consuming and relatively expensive. The results of the second, indirect estimation method may be less accurate compared to the direct investigation technique, but its scope of analysis is large and very efficient in terms of time and cost. A good example of the indirect estimation technique is analysis according to related industry, which exploits the structural relationships of different fields of industry as they pertain to the production of building materials. Lastly, the mixed technique blends the direct investigation and the indirect estimation methods according to the category to be analyzed. This technique sometimes utilizes results of indirect methods which had used the outcomes of direct investigations, as deemed necessary for the subject or scope of analysis. In other words, for important categories the base units are produced from direct investigations, and for other categories the base units from the results of indirect estimation techniques are used. Table 5 shows the comparison of their relative advantages.

Table 5
Calculation methods for database construction.

LCA Software	Input/Output	Others
EcoQuantum (NL)	EIOLCA (US)	Advanced Building Technologies (US)
IVAM (NL/EU)	NIRM (JP)	Harris Directory (US)
SimaPro (NL)		Oikos
Athena (CAN)		Energy Audit (AUS)
SIB LCA		
Boustead (UK)		

3. Organization of Life Cycle Assessment Programs

3.1. Main components

The requirements of an LCA Program to satisfy the above estimation techniques for calculation of base units, whether consumer products or building materials, are as follows.

First, it must be inclusive of a building's life cycle, which is categorized as the construction stage, the operation & maintenance stage, and the demolition & dismantling stage. Most of the existing LCA Programs domestic or abroad are designed to separate each stage of the life cycle for analysis, since the programs were fashioned for an individual material type or a consumer product to start with.

Second, the results of LCA can be expressed in various means based on what is being analyzed—in terms of energy consumption, or emission of global warming byproducts such as CO_2 or sulfur compounds, recyclability or reusability, and landfill requirements. As yet, there is no LCI database available for these mix of analyses, so an LCA Program to process all the factors is difficult. A separate LCI database is first called for each set of analyses, to enable a subsequent system for an LCA Program to include the base units at a later time.

Third, it is important for an LCA to select its purpose & scope of assessment. The scope to be included in the life cycle process of a building should be limited to the construction material resources required for the building, construction activities for modification & repair, lighting and energy requirements, and demolition & dismantling requirements. But CO_2 emissions from natural respiratory activities of human beings from construction activities are excluded. So, only factors directly related or consumed during the process of a building life cycle are selected for a limited scope of analysis.

3.2. Structural composition of an LCA Program

Based on the three requisite conditions for a Life Cycle Assessment as outlined above, the structural components of its program can be as follows.

First, an illustration of a building's life cycle process divided into stages of its construction, operation & maintenance, and demolition & dismantling, to show what is included at each stage is as shown in Table 6. Examples during the construction stage would include construction and raw materials, transportation to the site of construction, and the use of energy at the site for construction purposes. For the operation & maintenance stage, energy consumed for HVAC, lighting, and cooking, with required modification & repair as the building ages. Among these, it would be appropriate to divide the maintenance portion as routine versus large scale planned modifications, since large-scale maintenance activities are performed according to a long-term plan, and play a more important role than routine maintenance. Examples for the demolition & dismantling stage are equipment and construction

Table 6
Scope of analyses for an LCA Program.

Construction stage	Construction Material Production Construction Material Transportation Construction Site Transportation (Equipment & Power)
Operation & maintenance stage	Building Operation Maintenance Routine Maintenance Large Scale Modification
Demolition & dismantling stage	Building Demolition/Demolition Material (Equipment & Power) Transportation of Dismantled Material

Table 7
LCA LCI database computation method and scope.

	Object of Assessment		Method of Analysis
Energy Consumption & CO_2 Emissions	Construction Stage	Construction and raw materials necessary during the construction stage	Related Industry Analysis Method
	Operation & Maintenance Stage	Construction and raw materials used for modification & repair	Related Industry Analysis Method
		Heating & AC, Hot Water & Lighting	Energy Consumption & CO_2 Output Estimation Model Based on On-Scene Survey Data
	Demolition & Dismantling Stage	Construction and raw materials used for demolition & dismantling	Related Industry Analysis Method
		Machine & Equipment used for demolition & dismantling	Use of data based on interview of demolition & dismantling expert

Table 8
The classification of environmental load assessment of SUSB-LCA.

Stage	Classification	Sub-Classification
1. Construction	(1) Construction material production	① Construction work ② Public work ③ Facility work
	(2) Construction material transportation	① Transportation
	(3) Construction work of a site	① Construction site ② Public work ③ Gardening ④ Power consumption
2. Operation & Maintenance	(1) Use of a Building	① Power consumption ② Heating energy ③ City gas consumption
	(2) Maintenance	① Improvement and repair stage
3. Demolition & Dismantling	(1) Removal	① Removal
	(2) Disposal	① Loading ② Returning

material required for demolition, and includes their transportation for demolition, reclamation or reuse.

Second, the method of analysis for the LCA should be approached by each stage of life cycle. Available LCI database for construction and raw materials, energy consumption, and demolition & dismantling stages are diversified, and is difficult to establish from a single method of approach. Construction & raw material portion of the construction stage should be calculated using the analysis method as related by industry. Transportation to the construction site should be computed using on-scene investigation methodology. Furthermore, it would be realistic to estimate energy requirements for a construction site, such as electrical power and equipment, through the use of on-scene survey data.

To prepare LCI database for the modification & repair part of the operation & maintenance stage, a repair plan must first be in place. To devise this plan, a model to quantitatively express a building's rate of deterioration, and repair levels commensurate with aging, is needed. Energy consumed during the operational stage, such as for HVAC, cooking, and lighting, can for example, utilize energy consumption simulation data from the planning and design stage. But since this method does not reflect actual data but is rather an analysis based on assumptions, it lacks certain credibility. Therefore, it is necessary to develop a model for prediction of energy consumption or CO_2 emission, based on factors such as the number of units, floor area coverage, height of the building, and other variables.

For the demolition & dismantling stage, for the construction & raw materials used in dismantling, it is appropriate to use the related industry analysis method for calculation. For energy consumption of demolition equipment and such, on-scene survey data should be used. Transportation of waste should be investigated for *mean* waste production according to a type of building usage, to initially make an assumption to calculate the base unit. Table 7 shows LCI database calculation methods and scope according to the stages of a building's life cycle.

4. Characteristics of an LCA Program

An LCA Program must include a building's life cycle, and be devised to permit input and output of LCI database for the respective stages of this life cycle. Furthermore, it is necessary to allow comparison between alternatives, and to show the results of analyses in a quantitative format. For this purpose, it should be able to present the results of analyses not only as aggregate quantities, but also as a function of base unit dimensions of floor area. Fig. 1 is a summary of the basic components of an LCA Program according to its composition. As shown in Fig. 1, depending on its composition, an LCA Program is divided largely into the components of entering basic characteristics of the building to be analyzed, analysis conditions for the LCA, entering related data for analysis, output of analysis results, and the LCI database (Table 8).

4.1. Input for building specifications and analysis conditions

Among the program components, the file accepts input for building specifications and analysis conditions. Basic input specifications for a building to be analyzed are its name, type of usage, physical location, structure, building dimensions, total area, landscaping ratio, etc., and are utilized at the end of analysis to express

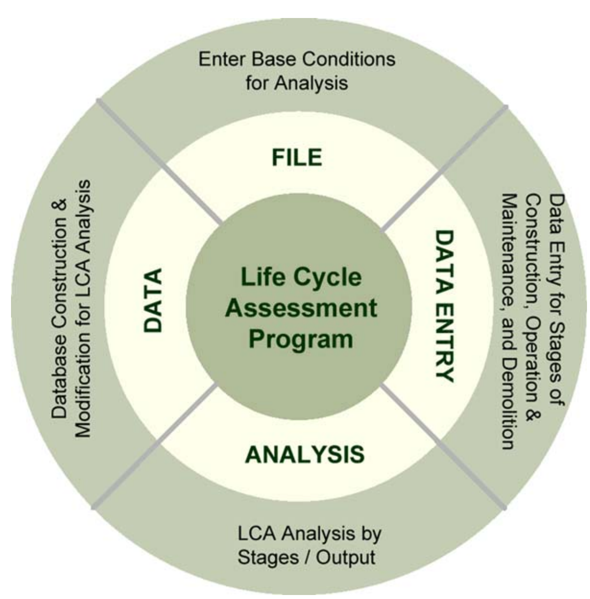

Fig. 1. Composition of an LCA Program.

Fig. 2. Input format of building general data.

base units as a function of floor area dimensions. Among the contents consisting of the file, analysis conditions include all basic assumptions for LCA. Stages of analyses are divided into main components of basic design, construction, and operation & maintenance stages. A life span for a building must be selected in order to analyze energy consumption and CO_2 emissions for the time period given. Other conditions are divided for the type of HVAC, facility installations, electrical and mechanical systems (Figs. 2 and 3).

4.2. Input for evaluation information (construction stage, operation & maintenance stage, and the demolition & dismantling stage)

For the data input portion, information required for the LCA are entered. Here, they are divided into the construction stage, operation & maintenance stage, and the demolition & dismantling stage, to enter data necessary for each separately. The construction stage is divided for entry as building construction, landscaping, and

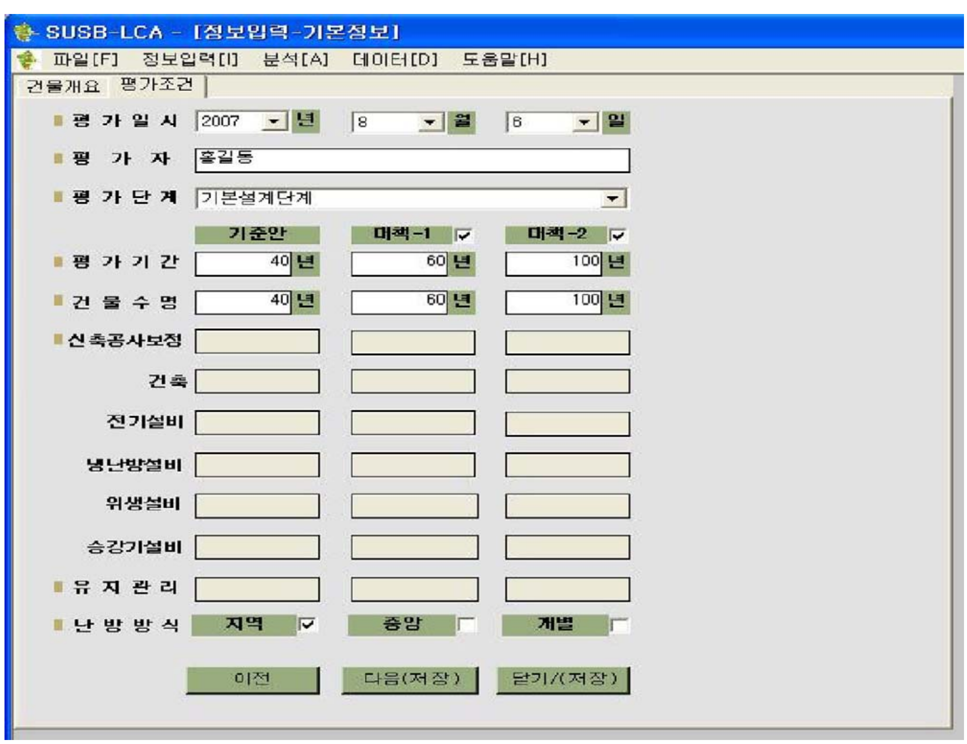

Fig. 3. Input of assessment conditions.

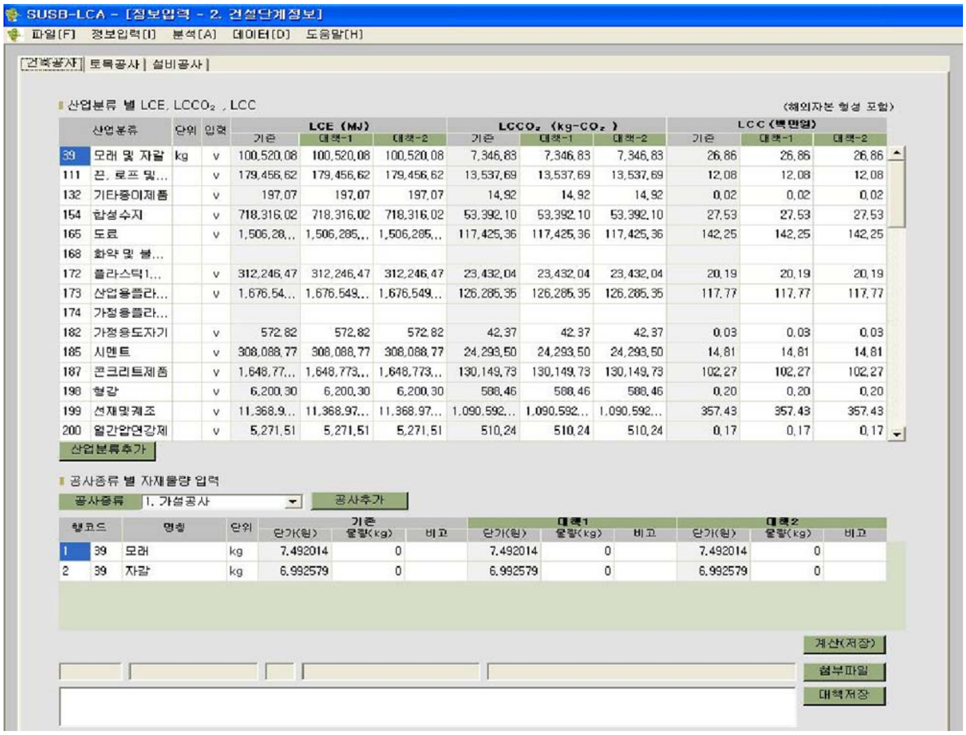

Fig. 4. Composition of data input for the construction stage.

facilities work, and is designed to decipher each type of construction by its common type. The operational stage includes all energy source types used for apartment buildings. Heating is divided into types as regional, central, or individual unit heating, with the amount of electrical energy for lighting, and city gas for food preparation to be entered.

For the operational stage, data for the annual electrical demand, annual heating energy expenditure, and annual city gas requirements are entered. A system is in place to facilitate assessment of alternative improvements to the existing plan by entering data for two alternative methods (Figs. 4 and 5).

Data entry for the demolition & dismantling stage is comprised of transportation distance for waste material disposal, transport capacity of vehicles, fuel cost, and the amount of waste production, among others. The standard mode of transportation for the waste material is based on an arm-roll truck model.

Fig. 5. Data input for the operational stage.

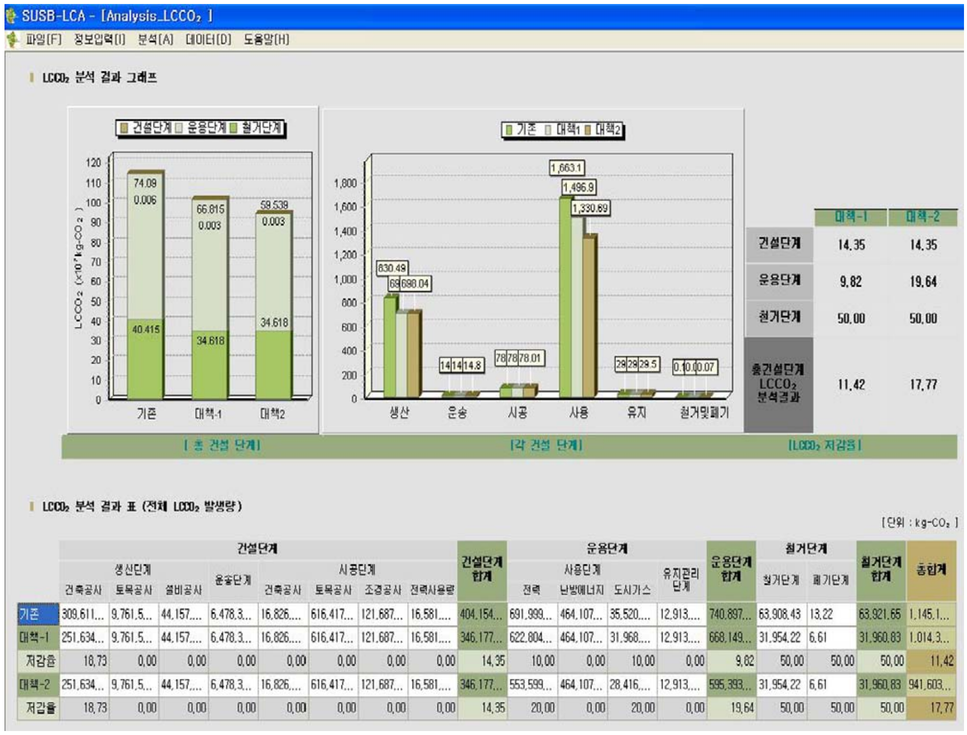

Fig. 6. Output format of analyses results.

4.3. Results of analyses and LCI DB

Results of analyses are presented for the building's life cycle energy, life cycle CO_2, and life cycle cost, in tabular format of their sum total. They are shown to allow comparison of the improved plan against the existing plan (Fig. 6).

The LCI database for an LCA Process consists of classifications for industry sectors, basic units of energy source types, and by types of construction [15,16]. The category for the sector of industry is designed to reflect computations of energy consumption and CO_2 base units for the construction stage, and construction & raw materials for modification & repair. Base units by types of energy source serve as primary input data for the computation of CO_2 emission base units from fossil fuel & electrical energy usage. The types of construction were separated to delineate the degrees of construction resulting from each of the building construction,

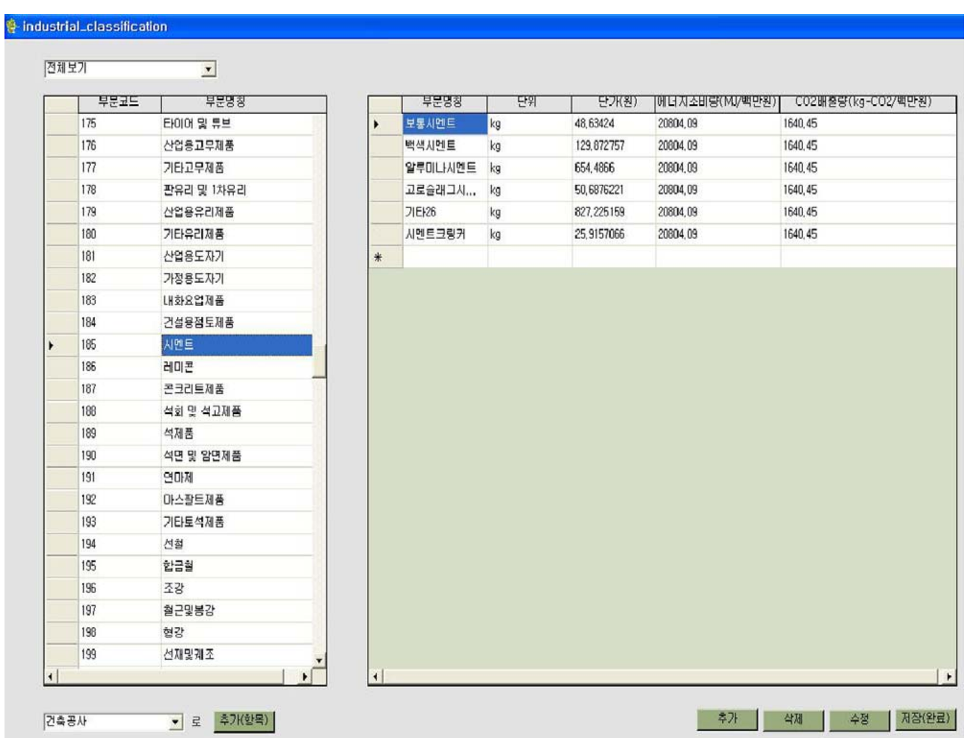

Fig. 7. Composition of LCI database.

landscaping, and facilities work comprising the construction stage. The composition of an LCI database is as shown in Fig. 7.

5. Conclusion

Recent interest and efforts for the environment clearly indicate that building constructions can no longer afford to damage the environment, but must seek to coexist with the environment. Rather than indiscriminate developments in the name of improving human living conditions, constructions compatible with environmental preservation are encouraged.

Building constructions possess life cycle stages of construction, operation & maintenance, and demolition & dismantling. It continually affects its surroundings from construction on, until its final demolition. Therefore a decision needs to be made to minimize its effects on the environment, from the planning and design stage, to reflect the life cycle of a building construction. The Life Cycle Assessment (LCA) method to analyze a building construction's influence on its surrounding environment requires a myriad of basic data, and much time and effort for application. To prevent such an involved process for analysis, the development of a program is necessary to facilitate the LCA of a building at the planning and design stage.

This paper aimed to develop an LCA Program for the building's planning stage. The results of our research are summarized as follows.

(1) A comparison of LCA Programs available domestically and otherwise for their characteristics shows most of them to have been designed for applications to consumer products, with relatively short life cycles, such that their application to durable entities such as building constructions with long life span is problematic. Therefore, for building constructions with such long life spans, it is deemed appropriate to separate the life cycle into stages of construction, operation & maintenance, and demolition & dismantling for analysis. Consequently, an LCA Program for applications to building constructions should consist of life cycle stages in its design.

(2) An LCA consists of four main stages, of its purpose & definition, inventory analysis, impact assessment, and improvement analysis. Among these, the impact assessment and improvement analysis results are variously expressed in terms of its purpose for analysis, such as for assessment of soil pollution, water quality degradation, or effects from waste material disposal. An SUSB-LCA Program is designed around the stages of purpose & scope, and inventory analysis [17]. For the other two stages, continual research is required to perfect the program to facilitate various purposes for analyses.

(3) Base unit data used in inventory analysis was constructed by dividing a building construction by its life cycle stages. Construction & raw material for the construction stage utilized the related industry analysis method, and the electrical, construction equipment and such utilized results from existing research. The operational stage used data by types of energy source for the same target apartment building construction. Base unit data for modification & repair type of maintenance used existing documents. Moreover, base unit data for the transportation of waste material during the demolition & dismantling stage used results from investigative analyses of transportation types and distance, by type of construction.

(4) Results from the operation of SUSB-LCA Programs are calculated to present data using base units of area dimensions, to facilitate ease of comparison and assessment between various types of proposals, expressed in terms of base unit energy consumption and CO_2 emission per unit area. The SUSB-LCA (Version 1.0) program for Life Cycle Assessment of building constructions focuses on the construction stage and operational stage of the life cycle, with their high shares of energy consumption and CO_2 production. Continual research to obtain base units of the other life cycle stage, for integration into the program will culminate in perfecting the program for Life Cycle Assessment of building constructions. Completion of the SUSB-LCA (Version 1.0) translates to the overall description of theory behind building Life Cycle Assessment, and amplifies the need for efforts toward continual improvements to each stage of life cycle.

Acknowledgements

This work was supported by Sustainable Building Research Center of Hanyang University which was supported the SRC/ERC program of MEST (grant # R11-2005-056-01004-0).

References

[1] Sjostrom C. Approaches to sustainability in building construction. Struct Concr 2001;3:111–9.
[2] Forsberg A. Fredrik von Malmborg. Tools for environmental assessment of the built environment. Build Environ 2004;39:223–8.
[3] Urie A, Dagg S. Development of a life cycle assessment (LCA) based decision-making tool for the assessment of building products. J Environ Assess Policy Manage 2004;6:153–76.
[4] Vorsatz DU, Danny Harvey LD, Mirasgedis S, Levine MD. Mitigating CO_2 emission from energy use in the world's buildings. Build Res Inform 2007;35:379–98.
[5] Li Z. A new life cycle impact assessment approach for building. Build Environ 2006;41:1414–22.
[6] Zhang Z, Shu X, Yang X, Zhu Y. BEPAS—a life cycle building environmental performance assessment model. Build Environ 1990;41:669–75.
[7] Urushizaki N, Mizuno M, Shimoda Y. The study on life-cycle waste and CO_2 emission from countermeasure of long-life building. J Architech Plan Environ Eng AIJ 2003;563:93–100.
[8] Excerpts edited from Kim DG. Basic environmental & economical comparison analyses of reinforced vs. concrete bridges using life cycle assessment methodology. Master Thesis. Korea Advanced Institute of Science and Technology; 1995: 23–5.
[9] Jonsson A, Bjoerklund T, Tillmann. LCA of concrete and steel building frames. Int J Life Cycle Assess 1998;3:216–24.
[10] Ardente F, Beccali M, Cellura M, Mistretta M. A LCA case study of kenaf-fibres insulation board. Build Energy Perform 2008;40:1–10.
[11] Japan Resource Institute. LCA methodology, energy. Resource 1996;6:26–5.
[12] Mohan Malhotra V. Reducing CO_2 emissions. Concrete International;September 2006:42–57.
[13] PR? Consultants BV, SimaPro user manual; 1999.
[14] PR? Consultants BV. SimaPro program reference; 1999.
[15] Åsa Jönsson. Tool and methods for environmental assessment of building products-methodological analysis of six selected approach. Build Environ 2000;35:223–38.
[16] Keizo Y. Redource consumption intensities based on 2000 input output tables: evaluation of building material consumption applying input output analysis (Part 2). J Environ Eng 2007;619:53–60.
[17] Soebarto VI, Williamson TJ. Multi-criteria assessment of building performance: theory and implementation. Build Environ 2001;39:681–90.